360 PINE STREET
SAN FRANCISCO CALIFORNIA 94104 M5-T
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W. W. DICKINSON CORPORATION

October 20, 1966

N67 18134
(ACCESSION NUMBER)
8
(PAGES)
CR-81791
(NASA CR OR TMX OR AD NUMBER)
(THRU)
1
(CODE)
14
(CATEGORY)
FACILITY FORM 602

Marshall Space Flight Center
National Aeronautics and
Space Administration
Huntsville, Alabama

HC $3.00
MF .65

Gentlemen:

Subject: Final Formal Progress Report, Contract NAS8-20613

This report will constitute the final formal progress report. Funding by NASA was terminated on September 14, 1966. W. W. Dickinson has continued the work at its own expense in view of the very encouraging results. During the period covering both NASA and W. W. Dickinson sponsorship, the following tasks were accomplished.

1. The system has demonstrated quantitatively and reproducibly the capability to measure and locate, nondestructively, the stress imposed by a highly-localized load on a .220 inch thick, 24-inch diameter, 36-inch long section of SI-C LOX tunnel section composed of 2219 aluminum and supplied by MSFC. A typical set of data is shown on Drawing 110-M-8 with a straight line approximated thereto. In many of the experiments, stress reversals could be observed so that the data is not necessarily a straight line function.

2. The measurement is made in terms of the test setup, schematically shown on Drawing 110-M-6 and pictured in previous progress reports, wherein the radial deflection at the point of force application is concurrently correlated with the acoustic beam bending or deflection on an oscilloscope (time-based display), a spectrum analyzer (frequency-based display), and a meter (analogue or digital numerical display).

3. With the wave directors at one fixed position in the setup as shown on Drawing 110-M-6, as the force was increased it was possible to inspect and cover a large zone of the cylinder and determine quantitatively on which of the time separated, multiple reflection paths the stress was varying. As shown on Drawing 110-M-7, the orientation of the multiple

reflection paths can be varied using a few wave directors combined in various transmit/receive arrangements. Since these two sets of wave paths can be oblique to each other, it is possible to localize the zone where such stress variation has occurred because the combination of wave path resects or triangulates the location of the stress induced beam bending.

4. By changing the support method for the tunnel section, combined with the localized radial stress imposition, it was possible to create stress reversal at some points concurrent with monotonic stress increase at others. When force was applied to the cylinder (reference Drawing 110-M-6), the one reflection signal was essentially unchanged; the three reflection signal monotonically decreased; the five reflection initially decreased, then increased above its original level, then decreased again but below its original level. The three reflection signal indicated a continuous uni-directional stress increase and resultant acoustic beam refraction; the five reflection signal indicated a stress reversal.

The theory upon which this work is based is described in our original proposal submitted to MSFC, a copy of the technical portion of which is enclosed and, for example, in the following references, copies of which are also enclosed: 1) "Ultrasonic Propagation in Deformed Single and Polycrystalline Materials", F.R. Rollins and R.R. Rowand; 2) "Nondestructive Measurement of Tensile and Compressive Stresses", Rabah A. Shahbender; 3) "Stress-Induced Anisotropy in Solids - the Acousto-elastic Effect," R. T. Smith. As indicated therein, acoustic velocity is proportional, to the square root of Young's Modulus divided by density; to the Lamé constants and to the third order (Murnaghan) elastic constants. These elastic constants are in turn functions of stress (and other variables).

The approach taken heretofore to apply ultrasonics to stress measurement has concentrated on the birefringent effects on the rotation of a plane of polarization of an ultrasonic shear wave. The problems with this approach are many: high attenuation of shear waves making test of large sections virtually impossible; boundary effects on scattering and mode converting shear waves; and high noise. The application of the Acoustic Spectrometer proposed and demonstrated made use of acoustic wave guide modes which were tuned to the test object to achieve low attenuation and which actually made use of the test object boundaries to create the desired wave guide modes. (These modes combined the three modes cited in Shahbender, p. 16.)

As the references cite, acoustic velocity changes but a few parts per hundred for significant changes in stress level based upon fundamental data. Since this change in acoustic velocity is directly related to the acoustic beam deflection (per Snells Law which applies to acoustic waves as it does to optics), the deflection of the acoustic beam as a result of stress is directly proportional to the change in acoustic index of refraction - local acoustic velocity before stress divided by local acoustic velocity after stress. $\frac{V - \Delta V}{V} = i$

In a section, which is highly homogeneous with regard to residual stress such as the LOX tunnel, the imposition of a local stress is a good simulation of a residual stress perturbation such as would be created by a magnetomotive forming operation. To assure no spurious data effects, many different experiments were run on different supports for the cylinder, different contact surfaces at the point of force application (metals and non metals of various contact shape), different wave director contact surfaces and materials, and different materials at parts of cylinder support on the test ring. It appears clear that the effects observed correlate only with stress imposition and are not the result of support, damping, edge effects, wave director contact and other factors.

Of particular interest is the demonstration of different effects for different numbers of acoustic beam reflections (reference Drawing 110-M-6). In turn, acoustic index of refraction is directly related to the change in acoustic velocity (ΔV) as a result of stress. Since the angular deflection induced by stress is small, the deviation is difficult to detect using conventional techniques.

Using the highly-collimated wave director of the Acoustic Spectrometer and its frequency-based data presentation, two related readouts are given: 1) Considering a fixed transmitter and receiver with a beam path connecting them and also passing through the stressed zone, the deflection of the beam causes its spectral distribution to shift as detected by the fixed receiver; 2) if the beam deflected at a stress concentration is reflected at edges of the test object, each reflection doubles the angular deflection and in turn enhances any beam bending resulting from stress. Thus the actual intensity (time-based data) of the received signal changes. (Considering that the angle of incidence equals angle of reflection in a reflection process, if the incident beam is deflected one degree, the reflected beam is also deflected one degree. As shown in Drawing 110-M-9, with multiple reflections between parallel reflecting surfaces such as the edge of a plate or cylinder, the point of reflection is moved as the beam is deflected so that multiple reflections serve to enhance the effects of beam bending. In the experimental work, both approaches (both the frequency and time based data) proved reproducibly usable under many test conditions and at many frequencies in the Marshall Space Flight Center LOX tunnel.

In summary, and in terms of the technical objectives cited in the contract, the following tasks were accomplished by WWD using the Acoustic Spectrometer System.

1. Cracks and porosity were detected and located in typical aluminum and titanium welded test objects of 1 inch and .065 inch thickness.

2. Quantitative numerical readout of stress, not merely an indication of highly stressed or lightly stressed areas was given in SI-C LOX tunnel sections. This numerical data was in a form such that it could be directly plotted as a conformal map of a test object.

Based upon these results, it appears that the Acoustic Spectrometer can be directly applied to nondestructive test stress measurement on a computer controlled survey basis.

As indicated, the work preceding the contract and that subsequent to termination has been funded by W. W. Dickinson so that the material covered in Drawings 110-M-6, 7, 8, 9, which is based thereon, is proprietary.

Sincerely yours,

W. W. DICKINSON CORPORATION

Wade Dickinson
President

Attachments:
1. **Drawings 110-M-6, 7, 8, 9**
2. **Technical proposal to MSFC submitted February 14, 1966 (with original only)**
3. **Three technical articles, referred to on page 2 (with original only)**

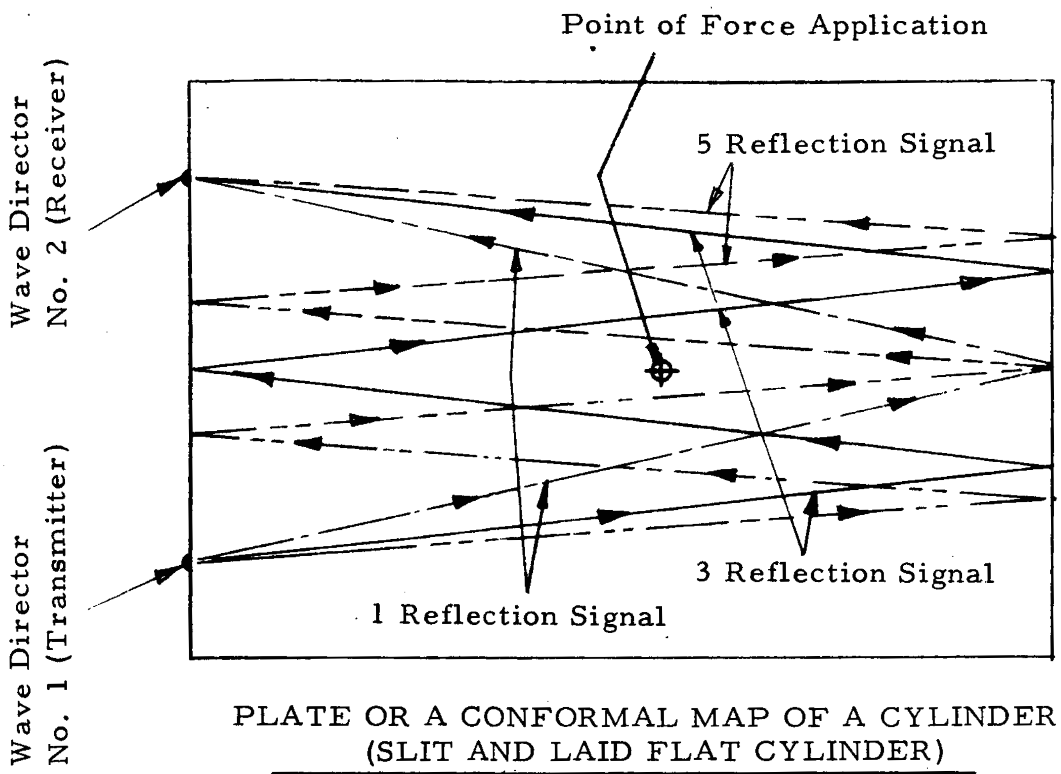
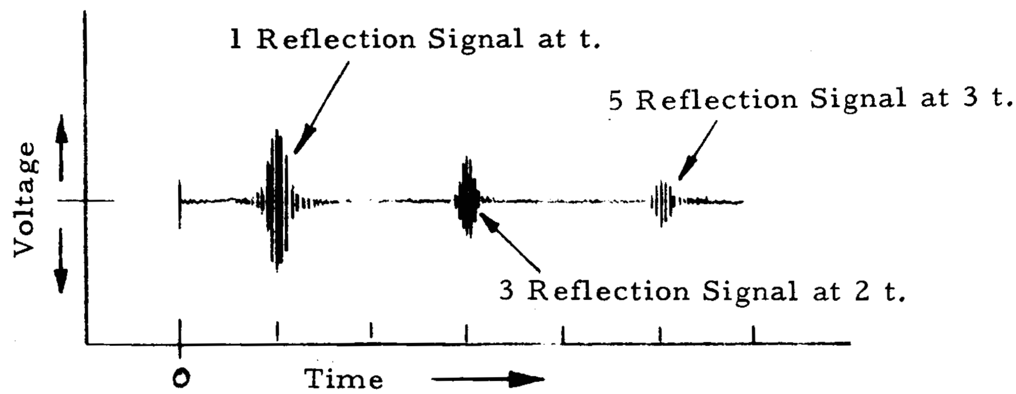


PLATE OR A CONFORMAL MAP OF A CYLINDER
(SLIT AND LAID FLAT CYLINDER)



CORRESPONDING OSCILLOSCOPE PATTERN

AXIAL NONDESTRUCTIVE MEASUREMENT OF IMPOSED STRESS BY ACOUSTIC BEAM REFLECTION ON .220" ALUMINUM 2219 MSFC LOX TUNNEL SECTION

PROPRIETARY DATA
PER COVER LETTER

W. W. DICKINSON CORPORATION
San Francisco, California

DRAWING 110-M-6

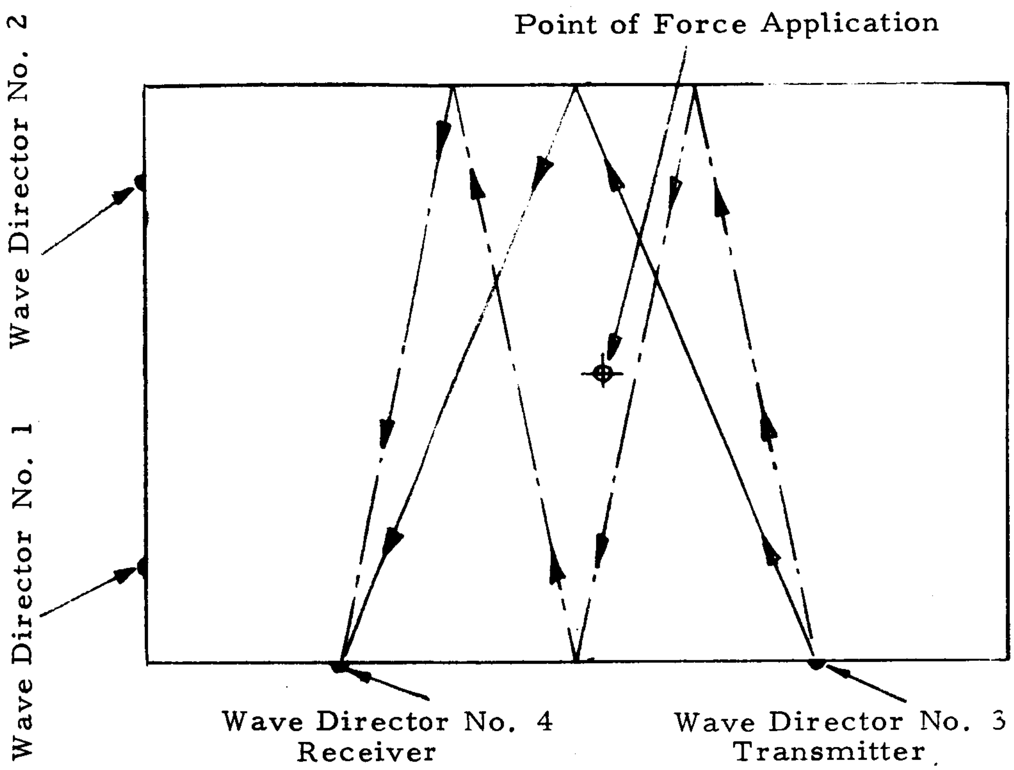


PLATE SECTION

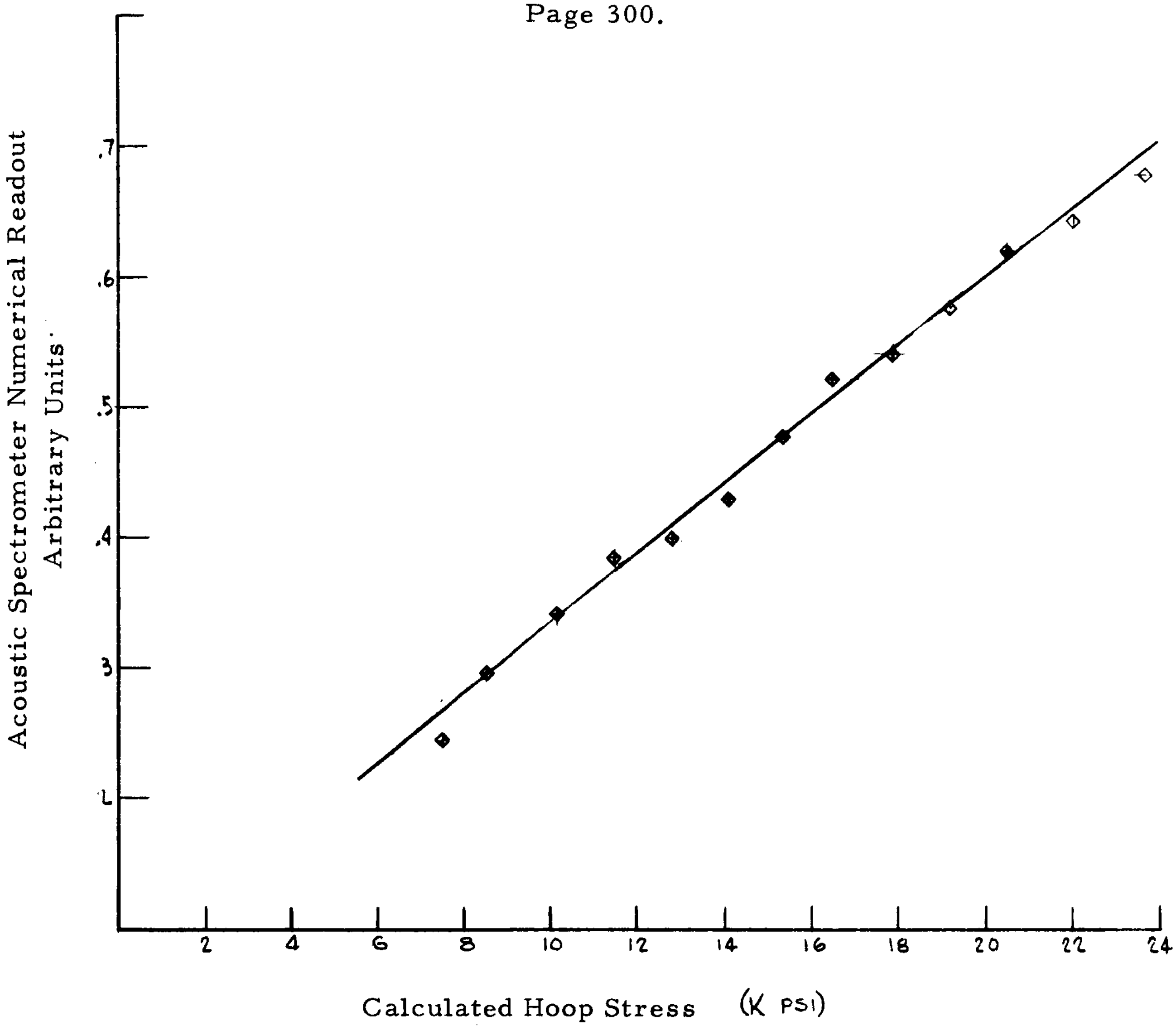
(For a cylinder, Wave Directors 3 and 4 would be at different location of edges of the cylinder to create oblique acoustic beam orientation with regard to Wave Director 1, 2 placement on Drawing 110-M-6)

TRANSVERSE NONDESTRUCTIVE MEASUREMENT
OF IMPOSED STRESS BY ACOUSTIC BEAM REFRACTION
ON .220" ALUMINUM 2219 MSFC LOX TUNNEL SECTION

W. W. DICKINSON CORPORATION
San Francisco, California

DRAWING 110-M-7

Hoop Stress Calculations
Based upon R.J. Roark,
Formulas for Stress and Strain,
4th Edition, McGraw-Hill.
Page 300.



ACOUSTIC SPECTROMETER STRESS ANALYSIS

W. W. DICKINSON CORPORATION
San Francisco, California

PROPRIETARY DATA
PER COVER LETTER

DRAWING 110-M-8

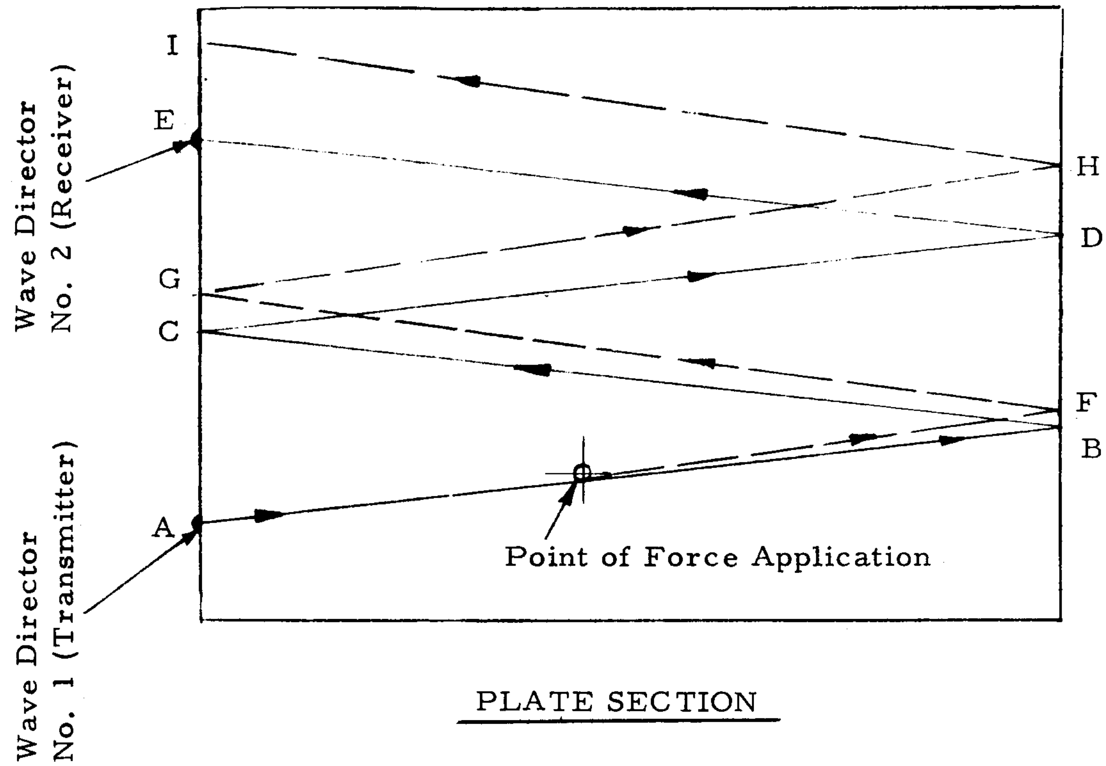


PLATE SECTION

Condition Before Stress Imposition - Path ABCDE

Condition After Stress Imposition - Path AFGHI

With a Fixed Transmitter at A and Fixed Receiver at E, when the Beam is refracted along Path AFGHI, the signal received at E changes both in amplitude and spectrum.

ENHANCEMENT OF ACOUSTIC BEAM REFRACTION BY MULTIPLE REFLECTION

W. W. DICKINSON CORPORATION
San Francisco, California

PROPRIETARY DATA
PER COVER LETTER

DRAWING 110-M-9